LCA Case Studies

Life Cycle Assessment of the District Heat Distribution System

Part 3: Use Phase and Overall Discussion

Part 1: Pipe Production [Int J LCA 9 (2) 130–136 (2004)]
Part 2: Network Construction [Int J LCA 10 (6) 425–435 (2005)]
Part 3: Use Phase and Overall Discussion [Int J LCA 11 (6) 437–446 (2006)]

Preamble. This series of three papers is based on research performed for the Swedish District Heating Association with the purpose of mapping the environmental life cycle impacts from the different phases involved in district heat distribution. **Part 1** concerns production of the district heating pipes while **Part 2** describes construction of the district heating pipe network. In **Part 3**, the use phase is evaluated based on heat losses from the network during heat distribution. Part 3 also includes a discussion in which the three evaluated life cycle phases are compared.

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DOI: http://dx.doi.org/10.1065/lca2005.08.225

Abstract

Goal, Scope and Background. The idea of district heating is to transport centrally produced heat to buildings where it is used for space heating and for domestic hot water generation. Water is used as a heat carrier. Many different heat sources are used to supply district heating networks with hot water. In literature, environmental studies on district heating mainly consider emissions from the heat generation; environmental impacts from the distribution system are seldom discussed. This paper is the third in an article series on the environmental impacts from the district heat distribution system. The paper presents an evaluation of the use phase of district heat distribution, focusing on long-term thermal performance of different district heating pipes. An overall discussion, in which environmental impacts from the different life cycle phases of district heat distribution are compared, is also presented.

Methods for the Use Phase Study. Environmental impacts from use of district heat distribution systems were evaluated based on heat losses from the networks, which depend on the long-term thermal performance of the district heating pipes. The heat losses cause environmental impacts from extra heat generation needed to cover the losses.
The long-term thermal performance of preinsulated bonded district heating pipes with steel tube, polyurethane foam insulation and polyethylene casing, depends on the thickness and quality of both the insulation and the casing. One important attribute of the foam is the blowing agent used. The blowing agent influences both the initial insulating capacity of the foam and the ageing characteristics, due to differences in migration rates of different substances through the materials.
Heat losses were calculated for different district heating pipe dimensions (DN25 twin pipe, and DN25, DN100 and DN500 Series 2 single pipes). Pipes with two different foam blowing agents (cyclopentane and carbon dioxide) were studied, taking into account the differences in long-term thermal performance of the foams. Concerning emissions from heat generation, two heat sources were considered: heat generation according to the average district heating fuel mix used in Sweden in the year of 2000, and heat generation using natural gas heat only boilers. The functional unit used is 100 m of district heat distribution network during 30 years of use.

Results and Discussion on the Use Phase. A short description of the inventory, some inventory results and a life cycle impact assessment are presented. Characterizations according to GWP, AP, POCP and resource depletion are given as well as two weightings: EcoIndicator99 and Ecoscarcity. The DN25 twin pipe network has about 25% lower environmental impacts from use than the DN25 Series 2 single pipe network. The district heating pipes insulated with cyclopentane blown polyurethane foam have a better environmental performance during use compared to those insulated with carbon dioxide blown foam (6–13%). This is partly dependent on a higher initial insulating capacity of the cyclopentane blown foam, but also due to a slower deterioration of the insulating capacity over time. For the two heat sources considered, different impact assessments give different indications to which option that is environmentally preferable.

Overall Results and Discussion on Pipe Production, Network Construction and Network Use Phases. A comparison of the three life cycle phases studied in this article series was made concerning four emissions, the four characterizations and the two weightings. The use phase represents over half of the total environmental impact for most, but not all, environmental parameters studied. It is important to keep the heat losses from the network down and to strive for heat sources with low environmental impacts. The larger the pipe, the larger is the relative impact from pipe production. The network construction phase has a relatively small contribution to the total environmental impact in most systems studied. However, the emissions during network construction often occur in residential areas and may therefore not be neglected when immediate nuisances and health aspects are considered. A very small change of the material flows in the production phase, the change between two different blowing agents (cyclopentane and carbon dioxide), can give dramatic results for the total environmental outcome for the district heating network because of a large change in influence on environmental impacts during use. The DN25 twin pipe network proves to be environmentally advantageous compared to the DN25 Series 2 single pipe network during all of the studied life cycle phases.

Recommendations and Perspectives. It is important to make sure that improvements in the production and construction phases do not lower the insulating capacity of the district heating system. A good initial insulating capacity, maintained over time, is important for the environmental performance of a district heat distribution network. Using DN25 twin pipes instead of DN25 Series 2 single pipes is a better choice, when possible, regarding all studied life cycle phases. The environmental impact from use of the district heat distribution system depends heavily on the type of energy source that is utilized to supply the network with heat.

Keywords: District heating pipe; heat loss; life cycle phases; network construction; pipe production; polyurethane foam insulation

Introduction

The idea of district heating is to transport centrally produced or collected heat to buildings where it is used for space heating and for domestic hot water generation. Water is used as a heat carrier. Many different heat sources are used to supply district heating networks with hot water. The most common fuels for district heating in Europe are natural gas and coal, but oil and renewables are also commonly used. Waste heat from industrial processes can also be utilized, as well as heat from waste incineration, geothermal heat and solar heat. Central heat generation in large plants gives possibilities to arrange highly efficient burning and flue gas treatment.

Up to now, studies of the environmental performance of district heating have mainly considered heat generation. Environmental impacts connected to the heat distribution system were highlighted during the phase-out of chlorofluorocarbons (freons), which were used as insulating gases in district heating pipes. However, the environmental discussion was limited to the use of these substances. This series of three articles focuses on environmental life cycle impacts from district heat distribution. The life cycle of the district heat distribution system can be considered to consist of four phases: production of district heating pipes, construction of pipe networks, use of the networks and post-use handling of the networks. In Part 1 [1] and Part 2 [2], environmental impacts from pipe production and network construction, respectively, were presented. In the present paper, the use phase of the district heat distribution system is considered. The paper also contains a summarizing discussion in which the environmental impacts from the three studied life cycle phases are compared. Post-use handling is not considered in the series.

In life cycle assessments of systems where large energy flows are involved during use, the use phase often proves to cause a large part of the total environmental impacts; e.g. for multifamily buildings in Sweden, the use phase has proven to cause approximately 70–90% of the total environmental impact from the dwelling's life cycle [3]. One might therefore anticipate that the use phase of the district heat distribution system has a larger relative impact than the other phases.

In this study, environmental impacts during use of district heat distribution systems are evaluated based on heat losses from the networks. Our research group is taking part in a long-term research effort to understand and describe such heat losses [4–7]. Heat losses from a specific district heating network may be determined from information on the heat generated and sold. However, this type of determination only gives information on the present heat losses from the specified network; information on a future situation is not received. Furthermore, information on differences in heat losses from different pipe dimensions, pipe types and laying alternatives used within the network are not obtained. The information will, because of its all-embracing nature, give small possibilities to understand details of the environmental performance of district heating networks. More detailed information can be obtained by determination of heat losses from physical properties of different district heating networks. The latter method was used in the present study.

1 Use phase: System description and inventory

Environmental impacts from the use phase of the district heat distribution system were evaluated based on heat losses from the networks. The studied networks consist of preinsulated bonded district heating pipes with steel service pipes insulated with polyurethane (PUR) foam, to avoid large heat losses from the networks. The foam layer is protected from mechanical damage and water intrusion by a polyethylene (PE) casing. The casing also functions as a barrier to gas diffusion, which deteriorates the insulating performance of the polyurethane foam insulation over time – a process often referred to as foam ageing. The heat losses were determined based on the long-term thermal performance of the district heating networks.

Different insulating gases can be used in the polyurethane foam insulation. At manufacturing, blowing agents, gases with low thermal conductivity and hence high insulating capacity, foam the polyurethane and become trapped within the cells of the foam. Carbon dioxide is a chemical blowing agent that always participates in the foaming to some extent and is therefore always present in the cells of a polyurethane foam. Carbon dioxide is created as a result of a reaction between one of the polyurethane precursors – isocyanate, and water. Physical blowing agents, such as cyclopentane, can be added to the polyurethane foam recipe. Cyclopentane vaporizes due to the temperature increase during polymerization.

Heat losses from DN25 twin district heating pipes and from DN25, DN100 and DN500 single district heating pipes with so-called Series 2 insulation thickness were calculated. Series 2 insulation thickness is commercially available and common in Northern Europe. The studied pipes are described in **Table 1**. A twin pipe contains two steel service pipes (one tube for supply and one tube for return water) within the same casing, while a single pipe only contains one service pipe (thus, two single district heating pipes are needed for a district heating circuit). More information on the studied district heating pipes is given in Part 1 of this article series [1]. Two different polyurethane foams were considered: cyclopentane blown and solely carbon dioxide blown. Cyclopentane is the standard blowing agent for the foam in district heating pipes commercially available in Europe today. Carbon dioxide was used as a sole blowing agent in the beginning of the chlorofluorocarbon phase-out.

Table 1: District heating pipes studied

Dimension Pipe design	DN25 Twin	DN25 Single	DN100 Single	DN500 Single
Steel tube outer diameter (mm)	33.7 [1)]	33.7	114	508
Distance between steel tubes (mm)	19	–	–	–
PUR foam thickness (mm)	–	35	52	89
PE casing, nominal outer diameter (mm)	140	110	225	710
PE casing thickness (mm)	3.2	3.2	3.8	12

1) Two tubes in one casing

Environmental impacts from the heat generation necessary to cover the heat losses from 100 m of pipe network (including both supply and return service pipes) during 30 years of use were modeled. The nominal lifetime according to the European standard for the district heating pipes is 30 years [8]. Two different heat generation options were considered: heat generation according to the average district heating fuel mix used in Sweden in the year of 2000, and heat generation in natural gas heat only boilers.

This study is not intended to be a comparison between networks with different service pipe dimensions, since they have different potentials to transport hot water and are thus not directly interchangeable. The functional unit used in this study does not take into account the capacity of the pipe system to transport heat. Generally, the heat loss [W/m pipe] is larger from a large pipe than from a small, as the large pipe has a large hot surface. But the relative heat loss (heat loss per transported energy) is lower for a large pipe than for a small pipe during normal operating conditions [9]. A pipe network always has to be designed based on the specific characteristics of the area the network is intended to serve, e.g. the heat density. Depending on the degree of usage of the pipes' water transporting capacity, the heat amount transported through the pipes in actual networks will differ over time.

This study is restricted to environmental impacts caused by heat losses that occur during use of the district heat distribution system. Maintenance of the distribution systems and operation aids are not considered.

1.1 Heat losses

The magnitude of the heat losses from a district heating network, given certain surroundings and operating temperatures, depend on the performance of the insulation of the district heating pipes. Heat losses were calculated by applying first-order multipole equations describing steady-state heat losses from pipes in the ground [10]. The pipes were assumed to be installed according to the guidelines of the Swedish District Heating Association, with a cover of soil of 0.6 m, which corresponds to laying in urban environments [11]. The soil temperature was assumed to be 7°C and the temperatures of the supply and return pipes 80°C and 45°C, respectively. A thermal conductivity of the soil of 1.5 W/(m·K) was applied [12].

The thermal conductivity of the polyurethane foam can be described as composed of contributions from radiation and from heat conduction through the polyurethane material and the cell gas. The cells of the foam are so small (<0.5 mm) that convection may be disregarded. The contribution from radiation and solid heat conduction may be considered constant over time and has been determined to be 0.012 W/(m·K) at a mean temperature of 50°C [13]. The contribution from cell gas conduction changes over time due to gas diffusion. The insulating gases diffuse out of the foam and air, with a comparatively high thermal conductivity, diffuses into the foam. Cell gas thermal conductivities for the different cell gas compositions were calculated by applying Brockaw's method with the coefficient set to 0.5 [14].

Initial cell gas compositions in polyurethane foams in commercial district heating pipes may vary, even for foams blown with the same blowing agent [6]. Regarding initial cell gas compositions in cyclopentane and carbon dioxide blown foams, best averages were estimated based on experiences of measurements of cell gas compositions (**Table 2**) [7,15]. In order to determine the change in cell gas composition over time, a model was used in which all transport resistance (polyurethane foam insulation and casing) is considered to be located to the casing, and diffusion is modeled as permeation through an effective layer of the casing's thickness (Model 1). The effective permeability coefficient applied for cyclopentane had been determined for a DN80 Series 2 pipe, while the effective permeability coefficients for the other gases had been determined for a DN150 Series 2 pipe. For pipes with different relations between foam and casing thickness, the effective permeabilities are slightly different. The calculations must therefore be considered as approximate. A more advanced model (Model 2), in which radial diffusion through the foam is considered and the polyethylene casing is taken into account as a resistance at the boundary, was used to check the reliability of the more approximate Model 1. Model 2 cannot handle twin pipes. For the single pipes, the two models gave similar results; the differences in heat losses determined with the two models were less than 10%, indicating that the approximate model is adequate for the purpose of this paper. Model 1 has thus, for conformity reasons, been used for all pipes in this study.

The purpose of this series of papers is to provide an in-depth description of environmental impacts from district heat distribution systems, making it possible to use the material in

Table 2: Estimated initial cell gas compositions in the carbon dioxide and cyclopentane blown foams studied, together with gas properties needed for the determination of heat losses

	Cyclopentane	Carbon dioxide	Nitrogen	Oxygen
Initial partial pressures in the foam at 50°C (kPa):				
carbon dioxide blown foam	–	140	1	0.5
cyclopentane blown foam	50	90	1	0.5
Thermal conductivity of the pure gases at 50°C (W/(m·K)) [16,17]	0.0145	0.0180	0.0278	0.0278
Model 1:				
Effective permeability (insulation + casing) (mol/(m·s·Pa)) [13,18]	$3.3 \cdot 10^{-17}$	$5.5 \cdot 10^{-16}$	$5.3 \cdot 10^{-17}$	$4.1 \cdot 10^{-17}$
Model 2:				
Effective diffusion coefficient in the foam at room temperature (m^2/s) [19]	$0.6 \cdot 10^{-13}$	$500 \cdot 10^{-13}$	$25 \cdot 10^{-13}$	$150 \cdot 10^{-13}$
Activation energy for the foam diffusion (J/mol) [19]	60 000	20 000	45 000	30 000
Permeability coefficient for the casing (mol/(m·s·Pa)) [19]	$23 \cdot 10^{-16}$	$8.6 \cdot 10^{-16}$	$0.65 \cdot 10^{-16}$	$1.9 \cdot 10^{-16}$
Activation energy for permeation through the casing (J/mol) [16,19]	40 000	30 000	40 000	35 000

other studies to estimate the environmental performance of actual district heating networks. Since only the heat distribution is considered and not the heating of houses, the heat generated for delivery is not taken into account, only heat losses. Had the heating of houses by different means been under study, the total heat generated would have been considered and impacts from the heat generation phase and distribution phase together would have been calculated for a certain heating effect in the building.

1.2 Heat generation

The heat losses correspond to environmental impacts from extra heat generation needed to cover the heat losses so that sufficient heat is delivered to the buildings served by the district heating network. The environmental impacts are greatly dependent on the kind of heat generation that is used to supply the district heating system with heat. Two different heat generation options were considered: average Swedish district heat in the year of 2000 (**Fig. 1**) [20] and natural gas heat only boilers [21–23]. Natural gas was the major primary energy source for district heat generation in the European Union in 1999 [24].

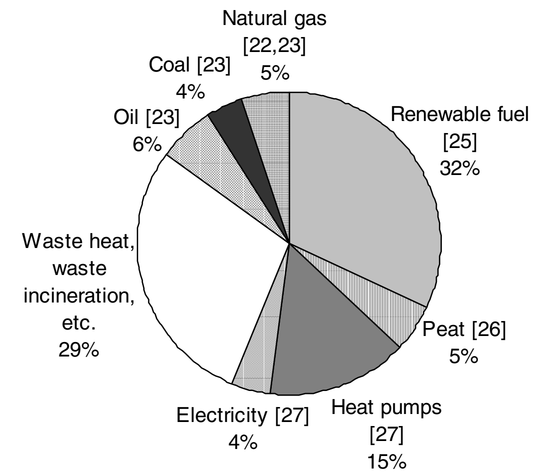

Fig. 1: Average Swedish district heat generation in the year of 2000. A coefficient of performance (COP, ratio of heat delivered by the heat pump to the electricity supplied) of 3 was assumed for the heat pumps. The references given in each category are to inventory data used. For 'Waste heat, waste incineration, etc.', no environmental impacts were allocated to the heat generation

2 Use Phase: Results and discussion

The initial thermal conductivity of the cyclopentane blown foam is slightly lower than that of the carbon dioxide blown foam; 0.029 compared to 0.030 W/(m·K) (**Fig. 2**). The insulating capacity of the foam deteriorates at different rates for the different pipes, depending on the pipes' dimensions and on the diffusion characteristics of the blowing agents. The average thermal conductivity over 30 years was determined and the heat losses from 100 m of pipe network were calculated (**Table 3**). The heat losses per meter pipe and year increase with up to 25% due to ageing during the 30 years of

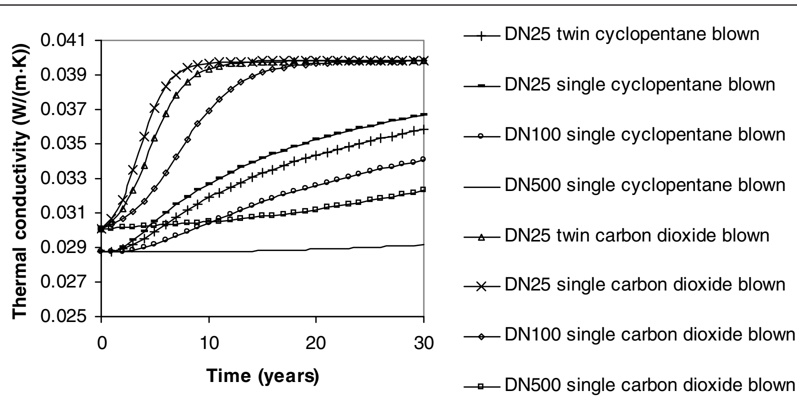

Fig. 2: Increase in foam thermal conductivity at 50°C over time due to foam ageing

Table 3: Average foam thermal conductivity at 50°C and corresponding heat losses from 100 m of pipe network over 30 years of use

	Cyclopentane blown	Carbon dioxide blown
Average foam thermal conductivity over 30 years of use [W/(m·K)]		
DN25 twin	0.033	0.038
DN25 single, Series 2	0.034	0.038
DN100 single, Series 2	0.031	0.037
DN500 single, Series 2	0.029	0.031
Heat losses from the district heating pipes [MWh/(100 m pipe network and 30 years of use)]		
DN25 twin	370	430
DN25 single, Series 2	500	560
DN100 single, Series 2	790	910
DN500 single, Series 2	1 500	1 500

service life of the pipes. So far, very few district heating networks have been taken out of service. This means that they may actually be used during a longer time period than the nominal lifetime of 30 years. If a time period of 50 years is considered instead of 30 years, the average annual heat losses increase with an additional 1–4% for the studied pipes.

Environmental impacts corresponding to extra heat generation needed to cover the heat losses were calculated. Four parameters from the inventory matrix are presented in **Table 4**. In **Tables 5** and **6**, characterizations and weightings of the full inventory matrix are given. Characterizations were performed for global warming potential (GWP, 100 years [28,29]), photo oxidant creation potential (POCP, high NO_x-background [29]), acidification potential (AP [29]) and resource depletion (RD, statistical reserve life [30]). Weightings were made according to EcoIndicator99 [31] and Ecoscarcity [32]. When considering the information in Tables 4–6, it is important to remember that the different pipe dimensions have different potentials to transport hot water. Thus, the overall larger figures for the DN500 pipe compared to the DN25 pipes do not indicate that it is better to build all district heating networks using small pipes. The choice of pipe dimension is determined by other constraints. However, two of the studied alternatives (DN25 twin and DN25 single) have the same heat transfer capacity and are thus possible to compare directly. The DN25 twin pipe network has about 25% lower environmental impacts from use than the DN25 Series 2 single pipe network.

The district heating pipes insulated with cyclopentane blown polyurethane foam have a better environmental performance during use than those insulated with carbon dioxide blown foam. This is partly dependent on a higher initial insulating capacity of the cyclopentane blown foam, but also due to a slower deterioration of the insulating capacity over time, as illustrated in Fig. 2. The environmental impacts from use for the DN25 Series 2 single pipe are 12% lower for the

Table 4: Inventory results for the use phase of district heat distribution, regarding emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) to air and emissions of compounds contributing to oxygen demand in water (measured as chemical oxygen demand, COD). Unit: kg/(100 m of pipe network and 30 years of use)

	DN25 twin				DN25 single				DN100 single				DN500 single			
	CO_2	NO_x	SO_2	COD	CO_2	NO_x	SO_2	COD	CO_2	NO_x	SO_2	COD	CO_2	NO_x	SO_2	COD
Cyclopentane blown Swedish district heat	25 000	110	69	0.32	34 000	140	92	0.43	54 000	220	150	0.68	99 000	410	270	1.3
Carbon dioxide blown Swedish district heat	29 000	120	80	0.37	38 000	160	100	0.49	62 000	260	170	0.79	110 000	440	290	1.3
Cyclopentane blown Natural gas boiler	84 000	83	0.99	–	110 000	110	1.3	–	180 000	180	2.1	–	330 000	330	3.9	–
Carbon dioxide blown Natural gas boiler	96 000	95	1.1	–	130 000	130	1.5	–	200 000	200	2.4	–	350 000	340	4.1	–

Table 5: Characterizations of the full inventory results for the use phase of district heat distribution according to global warming potential (GWP, kg CO_2 equivalents), photo oxidant creation potential (POCP, kg ethene equivalents), acidification potential (AP, kg SO_2 equivalents) and resource depletion (RD, kg resource equivalents/year). All numbers are given per 100 m of pipe network and 30 years of use

	DN25 twin				DN25 single				DN100 single				DN500 single			
	GWP	POCP	AP	RD	GWP	POCP	AP	RD	GWP	POCP	AP	RD	GWP	POCP	AP	RD
Cyclopentane blown Swedish district heat	27 000	21	150	97	37 000	28	200	130	58 000	45	310	210	110 000	83	570	380
Carbon dioxide blown Swedish district heat	31 000	24	170	110	41 000	32	220	150	67 000	52	360	240	110 000	88	610	400
Cyclopentane blown Natural gas boiler	84 000	2.6	59	470	110 000	3.5	79	620	180 000	5.5	130	990	330 000	10	230	1 800
Carbon dioxide blown Natural gas boiler	96 000	3.0	68	540	130 000	3.9	89	710	200 000	6.4	140	1 100	350 000	11	250	1 900

Table 6: Weightings of the full inventory results for the use phase of district heat distribution according to EcoIndicator99 (Ecopoints) and Ecoscarcity (Ecopoints). All numbers are given per 100 m of pipe network and 30 years of use

	DN25 twin		DN25 single		DN100 single		DN500 single	
	EcoIndicator99	Ecoscarcity	EcoIndicator99	Ecoscarcity	EcoIndicator99	Ecoscarcity	EcoIndicator99	Ecoscarcity
Cyclopentane blown Swedish district heat	1 500	$7.0 \cdot 10^7$	2 000	$9.3 \cdot 10^7$	3 200	$1.5 \cdot 10^8$	5 900	$2.7 \cdot 10^8$
Carbon dioxide blown Swedish district heat	1 700	$8.0 \cdot 10^7$	2 300	$1.0 \cdot 10^8$	3 700	$1.7 \cdot 10^8$	6 300	$2.9 \cdot 10^8$
Cyclopentane blown Natural gas boiler	5 600	$3.5 \cdot 10^8$	7 500	$4.6 \cdot 10^8$	12 000	$7.3 \cdot 10^8$	22 000	$1.4 \cdot 10^9$
Carbon dioxide blown Natural gas boiler	6 500	$4.0 \cdot 10^8$	8 500	$5.2 \cdot 10^8$	14 000	$8.5 \cdot 10^8$	23 000	$1.4 \cdot 10^9$

cyclopentane blown pipe than for the carbon dioxide blown pipe, 13% lower for the DN100 Series 2 single pipe, 6% lower for the DN500 Series 2 single pipe and 13% lower for the DN25 twin pipe. As the change in the foam's thermal conductivity is slower for long diffusion paths, the difference in environmental performance between the two blowing agents is more dependent on the difference in initial insulating capacity for the DN500 pipe dimension than for the smaller pipe dimensions (see Fig. 2). For the DN500 pipe, the difference in heat losses between the two blowing agent alternatives is smaller than the truncation and can therefore not be discerned in Table 3.

The environmental consequences of the heat losses and the differences between different pipes are dependent on the type of heat generation. If the heat used can be considered available without any environmental impacts, the insulating capacity has no environmental importance; this is to a large extent the case on Iceland where one can observe an abundance of geothermal energy and where geothermal heat is distributed in pipe systems with little if any insulation. In all other cases, the heat losses from the pipes during use correspond to environmental impacts. One should bear in mind that the heat source may change during the network's service life. In order to better understand the influence of heat generation, two scenarios were considered in this study; heat generated with the Swedish average district heating fuel mix in the year of 2000 and heat generated by natural gas boilers (heat only).

Regarding the four emissions shown in Table 4, only the carbon dioxide emissions are larger for natural gas heat generation than for average Swedish district heat generation. From Table 5, it can be seen that two of the characterization methods used favor average Swedish district heat production (GWP and resource depletion) and two of the methods favor natural gas (POCP and AP). In a characterization according to GWP, the difference in environmental impact is mainly due to the difference in carbon dioxide emissions; for both types of heat generation, the contribution from carbon dioxide emissions to GWP is much larger than the contributions from other emissions. With Swedish district heat, less fossil carbon is released compared with natural gas boilers. In the resource depletion characterization, the total dependence on fossil fuels gives a worst case for the natural gas heat generation. Average Swedish district heat comes out worse than natural gas in the POCP characterization, mainly due to larger emissions of carbon monoxide (the main contributing activity is the combustion of renewable fuels) and non-methane volatile organic compounds (NMVOC, where the main contributing activity is the production of light fuel oil). The AP characterization is influenced mainly by sulfur dioxide and nitrogen oxides emissions. The impact is largest for average Swedish district heat, where the sulfur dioxide emissions are derived mainly from combustion of comparatively small amounts of hard coal and peat in the fuel mix, while the nitrogen oxides emissions are largely connected to renewable fuel combustion. The noticeable influence on some environmental parameters from the use of renewable fuels indicates that renewability is not reason enough to consider a fuel to be environmentally friendly. Renewable fuels should preferably be combined with best available technology.

From Table 6, it can be seen that both weighting methods used in this study favor average Swedish district heat generation over natural gas, although for different reasons. In the EcoIndicator99 weighting, natural gas and oil resource use and emissions to air of carbon dioxide and nitrogen oxides are dominant for the two heat generation methods. The natural gas heat generation is the least favorable, mainly due to natural gas resource depletion and due to carbon dioxide emissions. The result from the Ecoscarcity weighting is dependent on the amount of hazardous waste reported for the use of natural gas. Regarding Swedish average district heat, it can be noted that the emission of cadmium to air from coal combustion gives a noticeable contribution to the total weighted result.

Given a specific pipe dimension, the differences in environmental impacts are typically larger between the two choices of heat generation than between the two choices of polyurethane foam insulation.

3 Use Phase: Conclusions

The long lifetime of the district heating pipes makes it important not only to consider the initial insulating performance of the district heating pipes, but to also take into account the long-term thermal performance of the pipes. Comparing the carbon dioxide blown and the cyclopentane blown foam, the cyclopentane blown foam is the most favorable, because it demonstrates both a higher initial insulating capacity and slower ageing. The environmental impacts from the studied cyclopentane blown networks are 6–13% lower than from the carbon dioxide blown networks.

The type of heat generation and the choice of insulating gases in the polyurethane foam have large influences on the environmental performance during the use of district heating networks. For each given pipe dimension, the differences in environmental impacts are larger between the two choices of heat generation than between the two choices of polyurethane foam insulation. This means that it is important to keep heat losses down and thus always good to have well insulated pipes, but, even for low heat loss alternatives, it is very important to strive towards as environmentally friendly a heat generation as possible. It shall be kept in mind that the energy source used to supply heat to the network might change during the service time of the network.

Two different designs of district heating pipes were studied: single and twin pipes. For the DN25 dimension, the environmental impacts during use are about 25% lower for a twin pipe network than for a single pipe network with Series 2 insulation.

4 Overall Results and Discussion

The information concerning environmental impacts from the different phases of district heat distribution presented in the different parts of this article series is discussed here as a whole. The data is given for 100 m of district heat distribution network, including both supply and return pipes, during 30 years of use. The results from the pipe production

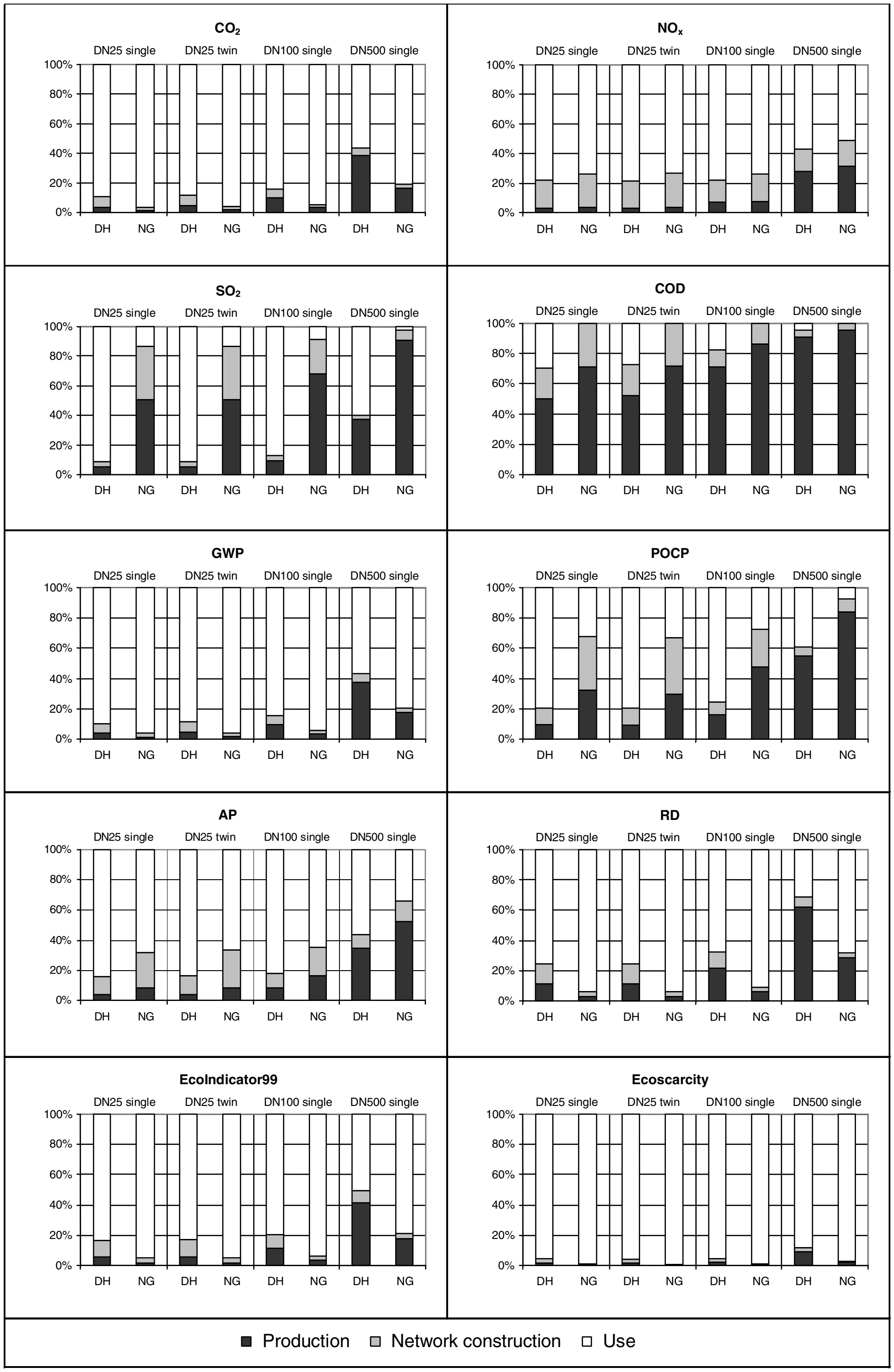

Fig. 3: Relative contributions from the different life cycle phases to emissions as well as characterized and weighted results for 100 m of district heat distribution networks in urban environments insulated with cyclopentane blown foam and run for 30 years with heat generated according to average Swedish district heat (DH) or natural gas heat only boiler (NG) scenarios

study [1] were recalculated into this functional unit using factors for pipe spillage during network construction of 4% for all pipe dimensions except the DN500 pipe, where a spillage of 1% was assumed. For more information on the network construction, see Part 2 [2].

In **Fig. 3**, the relative contributions from the different life cycle phases regarding the four emission parameters, the four characterizations and the two weightings, are presented for district heating networks with cyclopentane blown pipes installed in an urban environment and supplied with heat

generated as in the two heat generation scenarios (average Swedish district heat and natural gas heat only boiler). Carbon dioxide blown pipes would give a slightly larger contribution from the use phase than the cyclopentane blown pipes shown in Fig. 3.

From Fig. 3, the use phase can be seen to represent over 50% for most, but not all, environmental impacts studied. One exception is COD in water, where pipe production dominates. For sulfur dioxide emissions to air and for the POCP characterization, both the pipe production and the network construction phases have considerable contributions when heat is generated in natural gas heat only boilers. The network construction phase generally provides a minor contribution to the total, with a maximum of 38% in the POCP characterization for the natural gas heat supplied DN25 twin pipe network. However, emissions during network construction often occur in residential areas, since networks are often installed under streets or sidewalks, and should therefore not be neglected when immediate nuisances and human health aspects are considered. The larger the pipe, the larger is the relative impact from pipe production, due to the larger consumption of the different pipe materials. At the DN500 dimension, the contribution from pipe production is so large that the dominance of the use phase has disappeared for many environmental parameters.

In **Fig. 4**, the interest is focused on the difference between the two different blowing agents, cyclopentane and carbon dioxide. For the pipe production phase, only cyclopentane blown pipes were investigated. However, the necessary changes in material flows during production when changing from cyclopentane to carbon dioxide are very small. The production of cyclopentane (less than 1% of the weight of the district heating pipe) would be replaced by a small increase in the use of isocyanate. These small counteracting changes are not anticipated to change the outcome in a noticeable way. The blowing agents make up a very small part of the material included in a district heating pipe, but they have a large influence on the total outcome. There is no difference in the network construction phase, since carbon dioxide blown foam is always used when joints are foamed at installation, regardless of the blowing agent that is used in the pipes. For the GWP characterization, the difference between the two blowing agent choices in the use phase is larger than the sum of the impact from pipe production and network construction for both types of heat generation studied. Regarding the POCP characterization, this effect is not as strong, especially not regarding heat from natural gas boilers. Changing between two different blowing agents, a very small change of material flows, gives important improvements for the total environmental outcome for the district heating network due to lower heat losses during use. A difference between the life cycle phases that should be kept in mind is that emissions from the use phase occur over a period of 30 years, whereas production and construction phase emissions occur within a much shorter period of time.

The choice of heat generation has a more profound impact on the environmental performance than the choice of blowing agent. The difference between the two heat generation scenarios is much larger than the difference between the two blowing agent scenarios for the parameters shown in Fig. 4.

The DN25 twin pipe network proves to be environmentally advantageous compared to the DN25 Series 2 single pipe network during all of the studied life cycle phases for all environmental impacts considered; in **Fig. 5**, this is illustrated with GWP and AP characterizations. Using DN25 twin pipes instead of DN25 Series 2 single pipes is thus a better choice when possible. For larger dimensions, the twin pipe alternative need not be better than the single pipe alternative. The gain of the shared insulation in the twin pipe decreases with increasing dimension and the twin pipes eventually also become more difficult to handle because of their size.

In this series of papers, results are presented for four different pipes (see Table 1) with two different blowing agents, in two different environments. An actual district heating network is typically constructed using pipes of different dimensions and will often pass through different environments. The results presented in this article series can be used to model the environmental load from an actual district heating network when its layout is known. Different network designs can be studied.

In Part 2 of this series of articles, it was concluded that emissions derived from use of an excavator for excavation and refilling of the pipe trench have a major influence on the environmental impacts from the construction phase of a district heat distribution system, and thus the excavation work

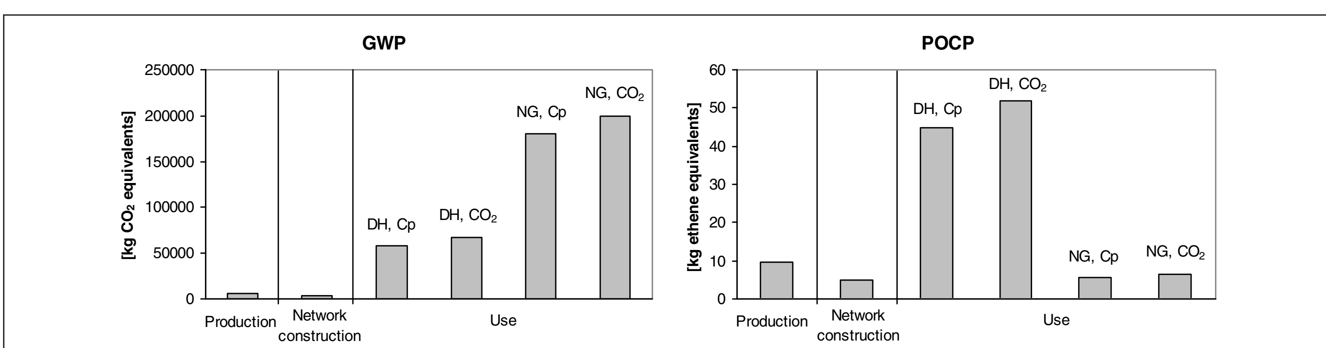

Fig. 4: GWP and POCP characterization results for 100 m of DN100 Series 2 single pipe district heat distribution network in urban environments used for 30 years. For the use phase, both heat sources (average Swedish district heat (DH) and natural gas heat only boiler (NG)) and both blowing agents (cyclopentane (Cp) and carbon dioxide (CO_2)) are shown

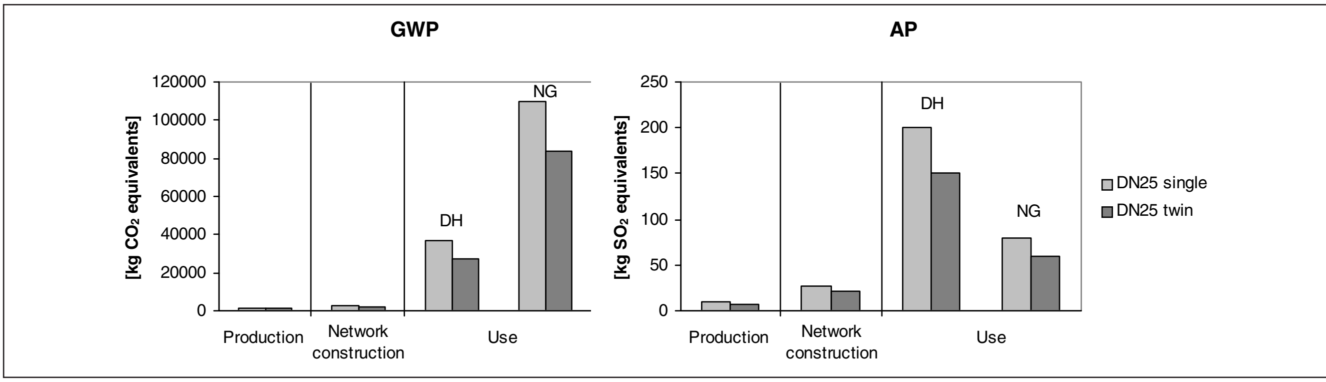

Fig. 5: GWP and AP characterization results for 100 m of district heat distribution network, built in urban environments using DN25 twin and DN25 Series 2 single pipes, insulated with cyclopentane blown foam and run for 30 years utilizing average Swedish district heat (DH) or natural gas heat only boilers (NG) as a heat source

for the pipe trench should be minimized. Use of twin pipes gives a narrower pipe trench than use of single pipes and thus reduces the need for excavation. The environmental impacts from excavation can also be reduced by a decreased laying depth, but at the same time as the excavation work is reduced, the insulating layer of soil above the pipes becomes thinner, which causes the heat losses during use to increase. The environmental balance between these two counteracting forces (less excavation and larger heat losses) is illustrated in **Fig. 6** for the DN100 cyclopentane blown single district heating pipe network with natural gas heat generation at soil cover thicknesses of 0.8, 0.6, 0.4 and 0.2 m. Depending on which environmental aspect is considered, the recommendations for optimal laying depth will vary. A decrease of the laying depth from the normal soil cover thickness of 0.6 m in urban environments to 0.2 m increases the yearly average heat losses by 4% for the DN100 cyclopentane blown pipe. It should be noted that the use of thicker insulation at shallower laying can compensate for the increased heat losses. For the DN100 pipe, a simultaneous decrease of the soil cover thickness to 0.2 m and increase of the insulation thickness to Series 3 will give a decrease in average yearly heat losses by 10%.

In order to get an indication of how large the contribution from a district heat distribution network is to the total impact from the heating of a building with district heat, an estimation was made. The heat losses from a district heat distribution system can vary widely, but is typically around 10% of the heat supplied to the customers [33]. If this is assumed for the cyclopentane blown distribution systems studied in this article series, the distribution system's share of the total impacts from the heating of a building with district heat (impacts from generation of heat and from the distribution system combined) would correspond to 12–20%.

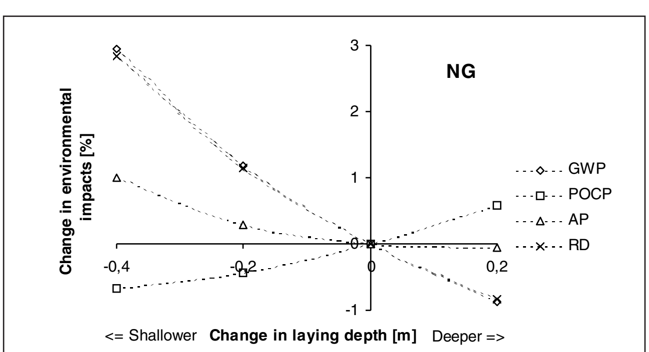

Fig. 6: Change in characterization results for varying soil cover 0,2–0.8 m (change in laying depth –0.4 to 0.2 m) for 100 m of DN100 district heat distribution network, insulated with cyclopentane blown foam and run for 30 years utilizing natural gas heat only boilers (NG) as a heat source

5 Overall Conclusions

There is no single phase in the life cycle of district heat distribution that always gives the main contribution to environmental impacts. Which phase that dominates depends on the type of environmental impact considered and the distribution situation, i.e. district heating pipe, installation area and means of heat generation. The use phase, however, dominates in many cases. It is therefore important to keep the heat losses from the network down and to strive to use heat sources with low environmental impact. The second most important contributor to the life cycle environmental impacts is pipe production, becoming increasingly important at large pipe dimensions.

The choice of district heating pipe influences both the environmental impacts from use, through the insulation capacity, and the environmental impacts from pipe production, through the materials that are required. It is very important to make sure that improvements in the production and construction phases do not lower the insulating capacity of the district heating system. A blowing agent, such as cyclopentane, giving the foam insulation a high initial insulating capacity that is maintained over time, may give a small increase of environmental impacts from the production phase, but a large gain in the use phase. In this article series, the twin pipe was found to be better than the Series 2 single pipe alternative for the DN25 pipe dimension.

A decrease of the laying depth will increase the heat losses during use, but will decrease the impacts from excavation of the pipe trench. Depending on which environmental aspects are considered, the recommendation on the optimal laying depth will vary.

Acknowledgements. Financial support from the Swedish District Heating Association and the Swedish Energy Agency is greatly appreciated.

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Received: October 22nd, 2004
Accepted: August 18th, 2005
OnlineFirst: August 18th, 2005